RECOMMENDATIONS FOR HIGHWAY CONSTRUCTION, MAINTENANCE, AND SERVICE EQUIPMENT WARNING LIGHTS AND PAVEMENT DATA COLLECTION SYSTEM SAFETY

by

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16. Abstract

This report presents the recommendations to improve the vehicle and equipment warning light policy for the Texas Department of Transportation, and improve the safety of the department's pavement data collection activities. Research efforts include a nationwide survey of vehicle warning lights and pavement data collection procedures, a motorist survey of their perceptions and interpretations of vehicle warning light color configurations, field studies of the effect of different warning light color configurations upon traffic operations, and a critique of current pavement data collection equipment and traffic control procedures. Researchers recommend that the current policy allowing blue lights to be used with yellow lights on selected vehicles and equipment should be retained. However, researchers do suggest other changes to the policy and provide recommendations to improve the safety of pavement data collection operations.

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IMPLEMENTATION RECOMMENDATIONS

SPECIAL VEHICLE WARNING LIGHTS

1. It is recommended that the policy regarding blue lights be expanded to explicitly state those characteristics which warrant the additional blue warning light color, such as:

   - Blue lights are intended to be applied to a vehicle or piece of equipment used for any activity that requires workers to be out of the vehicle while in a lane of traffic and without the presence of channelizing devices upstream of the vehicle to close the lane.

   - Blue lights are also intended to be applied to a vehicle or piece of equipment used during a moving operation in a travel lane that travels at a speed of less than 6 kmph (4 mph) or more than 50 kmph (30 mph) below the operating speed of traffic on a roadway. (researcher's note: the actual number used to define this criteria could be changed.)

2. Researchers recommend that the statement allowing the use of blue lights by maintenance foremen and assistant maintenance foremen be changed or eliminated. Researchers suggest the statement be reworded to allow blue lights on vehicles used for incident response activities (as opposed to incident removal or clean-up activities), regardless of who utilizes those vehicles. As a second option, the statement regarding maintenance foremen or assistant maintenance foremen could be embellished to indicate (possibly in parentheses) that "other personnel using these vehicles are allowed to activate the blue lights for the above-mentioned purposes."

3. Researchers recommend that legislation be proposed to designate TxDOT-authorized incident response vehicles as authorized emergency vehicles under Section 541.201 of the Texas Transportation Code (*1*).

PAVEMENT DATA COLLECTION ACTIVITIES

Researchers also recommend the following:

4. Place reflectors on all equipment that extends past the data collection vehicles to make the vehicles more noticeable to motorists.

5. Place Fresnel lenses on the back of all rear windows of data collection vehicles to provide drivers with better visibility.

6. Consider the use of the following magnetic signs during GPR pavement testing:

CAUTION TEST VEHICLE	EQUIPMENT IN FRONT

7. The older FWD units need to have the trailer retrofitted so that any necessary extra weights can be carried on the trailer, rather than in the data collection vehicle.

8. Ensure that all equipment and instruments inside data collection vans are fully secured. These items include tables and cabinets for mounting and setting equipment. Install top-loading fully secured storage bins for smaller items.

9. Each cabinet or table should be securely bolted to the vehicle floor as well as to the side of the vehicle. The vehicle frame can be used to secure the top of these items to the vehicle.

10. Removable items that are usually set on the floor (i.e, first-aid kit, tool box) should be strapped to the vehicle. For this purpose, vehicles should be equipped with straps at several locations.

11. During the data collection process (vehicle moving or stopped), each occupant should use a safety belt when inside the vehicle.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT). This report is not intended to constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the study was Dr. Gerald Ullman, P.E. #66876.

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1. INTRODUCTION

The Texas Department of Transportation (TxDOT) places significant emphasis on maintaining and improving worker and motorist safety, especially when work activities require that personnel be next to and within roadway traffic. Although much has been done to improve many aspects of worker and motorist safety during various work activities, the potential for more improvement exists in other areas. Questions have existed for some time about how to best use vehicle warning lights to delineate highway maintenance, construction, and service equipment. Although the need for vehicle warning lights is well understood and mandated by law, the large number of options available to TxDOT and other transportation agencies (rotating beacons, flashing incandescent or strobe lights, lens color, and mounting positions) places considerable pressure on policy makers to incorporate more and more lighting technologies on maintenance, construction, and service vehicles that are similar visually to those implemented on police and emergency vehicles (i.e., light bars, blue flashers, etc.).

Past studies have demonstrated the potential benefit of these warning light technologies with regards to conspicuity and/or information transmission (*2-4*). However, it is also apparent that overuse of any technology (including those employed for vehicle warning lights) can reduce their effectiveness. The question thus becomes how to decide if such devices should be used, on which vehicles they should be used, and under what conditions. In addition, questions exist as to whether it is beneficial to use more than just amber (referred to as yellow for simplicity purposes through this report) lights on certain types of service vehicles and equipment.

Past research has not extensively focused on worker and motorist safety during pavement data collection activities. The department maintains over 70 different pieces of equipment used to collect pavement data statewide. Most pavement data collection activities fall into either stop-and-go or mobile operations. However, pavement data collection activities have somewhat unique characteristics which may necessitate special considerations when developing appropriate traffic control and operating procedures. These characteristics include the following:

- They sometimes utilize much smaller vehicles (and fewer numbers of vehicles in a caravan) than are used in typical maintenance activities, and so may be much less conspicuous to approaching motorists;
- They may utilize special equipment that hampers motorists' efforts to pass the data collection vehicle (such as the ground penetrating radar which extends in front of the data collection vehicle);
- Although some activities may be classified as stop-and-go operations (such as the falling weight deflectometer), the actual time spent stopped at each location may be as short as a few seconds or minutes (making it difficult to provide static warning signs, cone tapers, or other indications to warn approaching motorists);
- Some data collection activities can be accomplished at near normal highway speeds and so do not generate the same speed differentials as those activities conducted at lower

operating speeds, but which still must be adequately protected through safe but effective vehicle warning lighting and traffic control procedures; and
- Some test procedures apply water to the pavement which can surprise an unsuspecting driver following behind and result in erratic behaviors.

Previously, very little research had been conducted to address these special traffic control needs and characteristics of pavement data collection systems. Also little research has been done to investigate how the major modifications made to "stock" pavement data collection vehicles might affect the safety of the workers operating that equipment.

RESEARCH OBJECTIVES AND TASKS

This report describes the results of a 17-month research effort for TxDOT by the Texas Transportation Institute to address some of the issues in both special vehicle flashing warning lights and pavement data collection systems. The specific research objectives were as follows:

1. Develop recommendations for improving TxDOT's warning light policy and practices for highway maintenance, construction, and service equipment; and
2. Evaluate pavement data collection equipment and operations, and develop recommendations for potential safety improvements.

To accomplish these objectives, researchers performed the following tasks:

- A nationwide survey of current DOT warning light and pavement data collection practices;
- A review and critique of current modifications to TxDOT pavement data collection vehicles;
- An assessment of motorists' perceptions and interpretations of alternative warning light color configurations;
- An evaluation of the effect of alternative vehicle warning light color configurations upon traffic operations;
- Identification of safety problems being experienced by pavement data collectors in the field; and
- Evaluation and improvement of current pavement data collection equipment, procedures, and traffic control used during these procedures.

This report summarizes the significant findings and recommendations from these activities. Further details regarding research activities can be found in research report TX-99/3972-1, *Highway Construction, Maintenance, and Service Equipment Warning Lights and Pavement Data Collection System Safety* (*5*).

2. MOTORISTS' INTERPRETATIONS OF VEHICLE WARNING LIGHT COLORS

One of the reasons for considering the use of additional colors and color combinations (other than just yellow) for special flashing warning lights on certain types of maintenance and construction vehicles is the assumption that these other colors imply a greater sense of danger or hazard to motorists. Traditionally, yellow flashing lights have been employed on vehicle warning lights, intersection beacons, and flashers mounted on signs and barricades in work zones. The level of hazard associated with these uses varies dramatically. Conversely, most states restrict certain colors of flashing lights to authorized emergency vehicles. Intuitively, one expects that these restrictions in effect teach motorists a flashing light color hierarchy over time as they encounter the different types of emergency vehicles and their associated warning light combinations. However, these assumptions have never been investigated in an objective manner. This chapter presents the results of surveys conducted in Dallas-Fort Worth, Houston, and San Antonio, Texas to assess motorists' interpretations of special vehicle warning light colors.

SURVEY DESIGN

The survey consisted of two parts. In the first part, motorists answered the following questions for each of several warning light colors/color combinations:

1. "If you saw flashing (color or color combination) warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?"

2. "What driving action, if any, would you take?"

Possible responses to the first question were as follows:

- Not hazardous at all,
- Somewhat hazardous,
- Moderately hazardous,
- Very hazardous, or
- Extremely hazardous.

Possible responses to the second question were as follows:

- No action,
- Take foot off accelerator,
- Tap brake,
- Apply brake gently, or

- Apply brake firmly.

Researchers queried motorists on each of the following colors/color combinations:

- Yellow,
- Blue,
- Red,
- Yellow/blue,
- Yellow/red,
- Blue/red, and
- Yellow/blue/red.

Researchers counterbalanced the presentation order of the various colors/color combinations to eliminate potential biases or the implication of increasing or decreasing hazard associated with a given order of presentation.

The second part of the survey asked subjects what colors of lights they expected to see on top of different types of vehicles. Vehicle types included the following:

- Police vehicle;
- Ambulance;
- Fire truck;
- School bus;
- Highway construction, maintenance, or service vehicle;
- Tow truck; and
- Motorist assistance or courtesy patrol vehicle.

TTI researchers traveled to Dallas-Fort Worth, Houston, and San Antonio to administer the survey at Department of Public Safety (DPS) driver's licensing stations. Researchers attempted to obtain responses from both younger and older subjects, and so the results reported in this chapter are believed to be fairly representative of the overall driving population in Texas.

SURVEY RESULTS

Motorists' Perception of Warning Light Colors

Table 1 summarizes the responses to the question about the level of hazard associated with each light color/color combination. Overall, the results do indicate that Texas drivers have learned a definite color hierarchy with respect to special flashing vehicle warning lights.

Table 1. Level of Hazard Associated with Various Light Colors/Color Combinations

Flashing Warning Light Color/Color Combination	Percent of Motorists Responding															
	"Not Hazardous"				"Somewhat Hazardous"				"Moderately Hazardous"				"Very Hazardous" or "Extremely Hazardous"			
	H	D-FW	SA	Avg.	H	D-FW	SA	Avg.	H	D-FW	SA	Avg.	H	D-FW	SA	Avg.
Yellow	13	11	18	13	40	52	49	47	39	30	27	33	8	7	7	7
Blue	17	18	30	20	33	29	23	29	35	33	34	34	15	20	14	17
Red	3	0	0	1	12	10	9	10	20	21	18	20	65	70	73	68
Yellow/Blue	15	8	11	11	29	38	32	33	39	34	48	39	17	20	9	17
Yellow/Red	9	8	3	7	22	27	17	23	38	33	42	36	32	32	39	33
Red/Blue	3	6	0	4	10	15	7	11	36	29	43	34	52	50	50	51
Red/Blue/ Yellow	5	1	5	3	14	10	0	13	31	27	23	28	49	62	59	56

H = Houston
D-FW = Dallas-Fort Worth
SA = San Antonio

Individually, yellow lights convey the least degree of hazard to motorists, followed by blue and then red. However, blue lights alone also received a significant number of "not hazardous" ratings (even slightly more than for yellow), indicating that its use alone does not convey a consistent level of urgency to all motorists. A few more of these "not hazardous" ratings came from the San Antonio location than from the other two locations. However, the differences in response by location for that color are not statistically significant at an 0.05 level of significance.

When two or more colors are combined in one display, the yellow/blue combination represents a slightly more hazardous situation to motorists than the yellow lights considered alone. However, statistical tests also indicate that the yellow/blue combination is perceived to represent a lesser degree of hazard than does the yellow/red combination. The red/blue combination yielded higher hazardous ratings than either the yellow/blue or the yellow/red combinations. Although the red/blue color combination received a large number of higher hazard rating by subjects, it was not as high as was obtained by just the red lights alone. Similarly, the red/blue/yellow combination yielded ratings that were not significantly different than the red/blue combination, but tended to be slightly less hazardous than those received for the red lights alone.

Table 2 presents a summary of survey responses as to the appropriate driving actions to take when encountering each flashing vehicle warning light color/color combination. Although responses differed between all but two of the color combinations in Table 1 (the red/blue and red/blue/yellow combinations were not significantly different), only a few color combinations generated significantly different driving action responses motorists considered to be appropriate when approaching the lights. For example, responses shown in Table 2 were not found to differ significantly between the yellow, blue, and yellow/blue color combinations. Overall, 40 to 45 percent of the subjects believed they should take no action or simply take their foot off the accelerator in response to seeing these colors on a vehicle. However, the yellow/red combination did result in different responses than did the yellow or the blue lights alone. Red lights alone yielded responses that differed significantly from the yellow, blue, yellow/blue, and yellow/red light combinations, but were similar to those obtained for the red/blue and red/blue/yellow light combinations.

In terms of location-by-location differences in the responses, San Antonio subjects generally selected a greater percentage of less-dramatic actions (i.e., no action or take foot off accelerator) for the yellow, blue, and (surprisingly) yellow/blue combination than did subjects in the other cities. Researchers do not know whether it is the ongoing extensive roadway construction activity in the region or other unknown factors which have reduced driver sensitivity to these lights in this city.

Table 2. Appropriate Driving Action Associated with Various Light Colors/Color Combinations

Flashing Warning Light Color/Color Combination	Percent of Motorists Responding															
	"No Action"				"Take Foot Off Accelerator"				"Tap Brake"				"Apply Brake Gently" or "Apply Brake Firmly"			
	H	D-FW	SA	Avg	H	D-FW	SA	Avg	H	D-FW	SA	Avg	H	D-FW	SA	Avg
Yellow	6	13	16	11	37	33	44	37	14	13	11	13	43	40	29	39
Blue	14	15	18	15	30	26	36	29	18	12	14	15	38	47	32	41
Red	2	0	0	1	11	14	7	12	9	8	7	8	79	78	86	80
Yellow/Blue	10	8	9	9	24	27	45	29	17	19	14	17	50	47	32	45
Yellow/Red	7	6	0	5	21	20	22	21	17	16	14	16	55	58	64	58
Red/Blue	2	4	0	2	14	13	16	14	16	11	18	14	69	72	66	70
Red/Blue/ Yellow	6	2	2	4	12	13	20	14	14	9	16	12	69	76	61	71

H=Houston
D-FW = Dallas-Fort Worth
SA = San Antonio

In summary, it does appear that motorists associate less hazard or danger with yellow flashing warning lights relative to some of the other colors and color combinations they may see. As a result, they also seem to perceive less of a need to slow down when approaching vehicles with flashing yellow lights than when approaching vehicles with yellow combined with red lights. Whereas it does appear that the presence of a blue light with the yellow light implies a greater sense of hazard to motorists, it does not appear that they associate a need to alter their driving behavior because of the presence of blue and yellow lights.

Motorists' Association of Warning Light Colors to Specific Vehicle Types

Researchers designed the second phase of the survey to investigate the types of warning light colors and color combinations motorists tend to associate with different types of emergency and other official vehicles. In this phase, they asked motorists to write down the special vehicle warning light colors they associated with each type of vehicle. Responses were completely open-ended. Subjects were not provided any type of list of appropriate colors or any other guidance (other than the colors investigated in part 1 of the survey). A summary of the major colors/color combinations that motorists associated with each vehicle type is provided in Table 3. Only those colors which received at least 10 percent of the responses are shown in the table. Consequently, the values in the various cells do not necessarily total 100 percent.

For the most part, the results in Table 3 are consistent with current Texas special vehicle warning light policies regarding color. Specifically, most motorists associate the color yellow with basic service vehicles (construction and maintenance vehicles, motorist assistance vehicles, and tow trucks). However, 11 percent of those surveyed in San Antonio identified the color blue with use in construction and maintenance vehicles. Responses from the other cities did not yield similar results with respect to blue lights. This result may help explain the association of blue lights with less dramatic driving actions by San Antonio subjects as shown previously in Table 2.

Responses for the motorist assistance vehicles also included other light color configurations besides yellow. Researchers expected this, as the patrols in each of the three locations surveyed typically utilize more than just the yellow lights only. Also, the distribution of responses did vary considerably from location to location. Again, researchers expected this, as there is some variance in how the different agencies outfit their motorist assistance vehicles. For example, the motorist assistance patrol in Houston is a consortium of several agencies and the private sector, and is manned by uniformed law enforcement officers (from the Harris County sheriff's office). Consequently, these vehicles are outfitted with a blue/red light combination that is typical for law enforcement vehicles in many jurisdictions statewide. In addition, TxDOT operates a service patrol in Houston after hours that is equipped with both yellow and blue lights. This may also help explain why the responses from the Houston subjects did not identify any one color or color combination as being predominant for that location.

Table 3. Warning Light Colors Associated with Various Vehicle Types

Vehicle Type	Flashing Warning Light Color/Color Combination	Percentage Responding			
		Houston	Dallas-Ft. Worth	San Antonio	Average
Construction, Maintenance, or Service Vehicle	Yellow	69	75	58	70
	Blue	-	-	11	-
Motorist Assistance Vehicle	Yellow	20*	56	58	42
	Blue	17	12	14	14
	Blue/Yellow	-	-	14	10
	Blue/Red	18*	-	-	-
Tow Truck	Yellow	74	65	76	70
	Red/Yellow	-	12	-	-
Police	Blue/Red	56	42	56	50
	Yellow/Red/Blue	-	17	12	13
	Red/White/Blue	12	10	-	-
	Blue	-	-	10	-
Ambulance	Red	43	30	46	38
	Red/Blue	10	13	-	10
	Red/White	26	19	12	21
	Red/Yellow	10	16	-	12
Fire Truck	Red	63	46*	78	58
	Red/White	18	15	11	16
	Red/Yellow	10	11	-	-

- less than 10 percent of the respondents
* percentage is significantly different ($\alpha = 0.05$) than the other two locations

The responses subjects provided regarding light colors on emergency vehicles also generated some interesting results. In particular, motorists do appear to recognize differences in warning light color combinations used by police vehicles and those used by other types of emergency vehicles. For example, motorists cited a red/blue light combination most often for police vehicles (by 50 percent of those surveyed), whereas the single color red was more often cited for ambulances and fire trucks. In fact, only 10 percent of motorists associated the red/blue light combination with an ambulance, and less than 10 percent did so for fire trucks. However, substantial differences in these responses are evident from location to location. In Dallas-Fort Worth and in San Antonio, for example, a red/blue/yellow light combination for police vehicles was the second-most frequently identified combination (behind the red/blue combination). In comparison, Houston subjects cited a red/blue/white combination for police vehicles second-most frequently. With respect to fire trucks, Dallas-Fort Worth subjects reported a wider variety of colors and color combinations and generated responses that were not consistent with those from Houston and San Antonio.

IMPLICATIONS OF RESULTS TO TXDOT VEHICLE WARNING LIGHT POLICY

The purpose of allowing blue and yellow lights on selected vehicles and equipment in the TxDOT vehicle warning light policy is the assumption that the use of the blue light added a greater sense of urgency and a need to be cautious by motorists as they approach the vehicle. The results of this survey do suggest that the combination of blue and yellow lights implies a slightly greater sense of hazard to motorists than does the yellow light alone. However, this greater sense of hazard does not necessarily translate into differences in how motorists believe they need to respond to the different color lights. In fact, when asked what action they should take in response to a yellow light in comparison to a yellow and blue light combination, no statistically significant differences in responses were found. Somewhat surprisingly, it is a yellow and red light combination on top of the vehicle which motorists say is indicative of a higher hazard condition and which implies to them a greater need to respond by applying their brakes. Although this configuration is not judged as hazardous as the red/blue/yellow configuration allowed for use on courtesy patrols, it does represent a more significant shift in subject perceptions from the yellow light only configuration than achieved by a yellow and blue light combination.

3. FIELD STUDIES OF ALTERNATIVE VEHICLE WARNING LIGHT COLOR CONFIGURATIONS

The survey results described in Chapter 2 suggest that motorists do indeed perceive differences in vehicle warning light color configurations, and believe they should respond differently to them. To determine whether these perceptions actually translate into differences in driver behavior, researchers conducted a series of field studies on five urban freeway sections in Houston and San Antonio, Texas. In each study, TxDOT maintenance or courtesy patrol vehicles were outfitted with different vehicle warning light color combinations and placed, one at a time, on a shoulder next to moving traffic with the lights activated. Consistent with current TxDOT policy, the warning light color combinations examined in this phase of the study were as follows:

- Yellow lights only,
- Yellow/blue lights,
- Yellow/blue/red lights (San Antonio courtesy patrol), and
- Blue/red lights (Houston motorist assistance patrol).

Researchers did not test a yellow/red light configuration in the field. The basic question to be answered in these studies was whether the use of different lighting configuration had an effect on operational behavior at all. The study encompassed both ends of the spectrum with respect to driver perceptions of hazard (the yellow light at the lesser end and the yellow/blue/red or blue/red light at the greater end), and so researchers expected it to provide an answer to that question. Furthermore, it was expected that the results from these configurations would allow some inferences to be drawn about whether a yellow/red lighting configuration could be beneficial.

A fourth combination, consisting of yellow and blue strobes mounted in the back window of a TxDOT sport utility vehicle and strobes mounted in the rear taillight assemblies (operating in a simultaneous double-flash mode), was also tested at two of the sites. To evaluate the effect that vehicle type itself has upon driving behavior, TTI was assisted in the research by officers with the Texas Department of Public Safety (DPS). These officers brought out their police cruisers (and their yellow/blue/red warning light) and allowed researchers to obtain data at the same locations as where the alternative warning light configurations on TxDOT vehicles were evaluated.

STUDY METHODOLOGY

At each of five study sites, researchers videotaped traffic approaching the vehicle from 150 to 450 m (500 to 1500 ft) upstream to determine vehicle speeds, traffic distribution by lane,

lane-changing activity, and brake activations under each of the flashing vehicle warning light configurations. Researchers collected approximately one hour of data at each site for each warning light configuration tested. The vehicles were tested on either the left or the right shoulder in either daytime or nighttime conditions (both daytime and nighttime conditions were evaluated at Site 1). Brake applications could only be determined during the nighttime studies, however. Furthermore, camera difficulties and other temporary problems did not allow all of the different types of data to be obtained from each of the five sites. Nonetheless, the data were sufficient to allow a fairly extensive evaluation to be completed in most cases.

SITE DESCRIPTIONS

Studies were conducted at a total of five different freeway locations in San Antonio and Houston. Data on some of the warning light configurations were also collected during a short-term maintenance activity in Dallas. Unfortunately, a less-than-ideal camera viewing perspective coupled with debris in the roadway upstream of the service patrol vehicles did not allow the data collected at that location to be used in the final analysis. Table 4 presents a summary of the roadway characteristics at each site.

Table 4. Summary of Study Site Characteristics

Site	Location	# Lanes	Shoulders?	Overhead Lighting?	Vehicle Location
1	I-410 EB @ I-10, San Antonio	3	partial left, full right	high-mast	beyond left shoulder
2	I-35 SB @ Division, San Antonio	3	full left, full right (narrowed at bridge)	N/A	right shoulder
3	I-610 EB @ Kirby, Houston	5	full left, partial right	high-mast	in exit ramp gore area
4	US 59 NB @ Hillcroft, Houston	5	full left, full right	high-mast	right shoulder
5	US 59 NB @ Shepard, Houston	5	full left, full right	high-mast	right shoulder

STUDY RESULTS

Effect of Warning Lights on Vehicle Speeds

Table 5 presents a comparison of average speeds of vehicles passing the test locations when the different vehicle warning light configurations were being displayed. These data represent the average of approximately 120 vehicles during each time period. Camera problems did not allow speed data to be obtained from Site 4 (US 59 at Hillcroft) in Houston, or during certain other portions of the study as illustrated in the table.

At two of the five sites tested, vehicle speeds when the yellow and blue light combination was displayed were significantly (8 to 10 kmph [5 to 6 mph]) lower than when only a yellow light was displayed. At the other three sites, speeds were not significantly different between these two warning light configurations. Interestingly, no statistically significant differences were found in average speeds at any of the sites when the yellow/blue/red (or blue/red) warning light configuration was compared to the yellow warning light only configuration. The yellow and blue strobes with red strobes in the vehicle tail lights did not yield a significantly lower speed at Site 1 relative to the yellow only configuration during either the daytime or the nighttime study period.

Table 5. Effect of Warning Light Colors on Average Speeds

Site		Average Speed, mph				
		Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1:	Day Night	68 60	71 58	71 58	66 60	N/A 61
2:	Day	61	56*	63	58	N/A
3:	Night	59	56	56[a]	N/A	58
4:	Night	N/A	N/A	N/A	N/A	N/A
5:	Night	60	54*	61[a]	N/A	59

* Significantly lower ($\alpha = 0.05$) than the yellow only light condition
[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration
N/A Data not available

Perhaps equally surprising was the finding that the presence of the DPS vehicle parked on the shoulder with its lights flashing did not affect speeds any more than the TxDOT vehicles. No statistically significant differences were found between speeds observed when that vehicle was present and when the TxDOT vehicles with yellow flashing lights were present. Average speeds at four of the five sites were not particularly excessive, even for the yellow light configuration, which may have been why the presence of the DPS vehicle with flashing lights did not have more of a significant effect. Unfortunately, daytime speed data were not available for the DPS vehicle at Site 1, where average speeds for the other warning light configurations were higher.

Effect of Warning Lights on Driver Lane Choice and Lane Changing

Researchers examined driver lane choices as a potential measure of performance regarding different vehicle warning light colors. They evaluated lane choice both in terms of the percentage of traffic in the lane closest to the vehicle warning lights, and in terms of lane-changing rates away from the lights (within the camera field-of-view). Table 6 presents the percentage of traffic in the lane closest to the flashing warning lights. Generally speaking, the different warning light color configurations had very little effect upon this performance measure. The only statistically significant differences detected occurred during the nighttime studies at Site 1, where lane percentages adjacent to the yellow/blue/red and yellow/blue strobe warning light configurations decreased slightly relative to the yellow light only configuration. As with the speed data, no significant differences were detected in the lane distribution when a DPS vehicle was used compared to the other warning light configurations.

Table 6. Effect of Warning Light Colors on Lane Distributions

Site		Percent of Traffic in Lane Next to Study Vehicle				
		Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1:	Day	33	34	36	39	34
	Night	39	35	33*	33*	36
2:	Day	33	35	39	33	39
3:	Night	16	19	19[a]	N/A	18
4:	Night	22	21	19[a]	N/A	N/A
5:	Night	11	11	12[a]	N/A	9

* Significantly lower ($\alpha = 0.05$) than the yellow only light condition
[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration
N/A Data not available

Table 7 shows the percent of traffic making a lane change away from the location of the study vehicle (i.e., to the left if the vehicle is on the right shoulder, towards the right if it is on the left shoulder). From these data, it is also apparent that the type of warning light configuration displayed had little, if any, effect on driver lane choice behavior. Site 3 did experience significantly higher lane changing rates away from the lights when blue and red colors were used in conjunction with yellow light (in comparison to the all yellow light configuration). However, this was not repeated at the other sites. At Site 5, the use of the DPS vehicle also yielded an increase in lane changing away from the vehicle, but this again was not replicated at any of the other sites.

Table 7. Effect of Warning Light Colors on Lane Changing Frequency

Site	Percent of Traffic Changing Lanes Away From Study Vehicle				
	Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1: Day Night	2.6 2.8	2.2 2.2	1.7 1.9	2.5 5.6	5.4 2.9
2: Day	6.3	3.9	2.1	1.1	N/A
3: Night	12.6	20.8*	20.7*[a]	N/A	15.7
4: Night	11.2	12.5	10.4[a]	N/A	N/A
5: Night	4.8	0.0	3.6[a]	N/A	18.5*

* Significantly higher ($\alpha = 0.05$) than the yellow only light condition
[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration
N/A Data not available

Effect of Warning Lights on Brake Activations

The final performance measure examined was the frequency of brake light activations for motorists approaching the various vehicle warning light color configurations. These comparisons could only be made for those studies conducted at night. Table 8 presents the percent of brake light applications under each configuration at each of the nighttime study sites. At three of the four sites where nighttime data were collected, the yellow/blue/red warning light configuration resulted in a higher braking percentage than the yellow light only. The yellow/blue configuration also resulted in a significantly higher braking percentage (relative to the yellow only configuration) at one site. At two of the three sites where data were available for the DPS vehicle, brake light activations were also significantly greater than they were when the yellow light only on the TxDOT vehicle was displayed.

Table 8. Effect of Warning Light Colors on Brake Light Activations

Site	Percent of Traffic Activating Brake Lights				
	Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1: Day	N/A	N/A	N/A	N/A	N/A
1: Night	3.9	9.3*	9.5*	9.1*	4.5
2: Day	N/A	N/A	N/A	N/A	N/A
3: Night	1.6	5.4	7.9*[a]	N/A	15.8*
4: Night	14.9	14.0	20.4*[a]	N/A	N/A
5: Night	2.2	3.0	4.2[a]	N/A	11.3*

* Significantly higher ($\alpha = 0.05$) than the yellow only light condition
[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration
N/A Data not available

Although researchers did not measure pavement illumination levels during these studies, it did appear that the overhead lighting was a little brighter at Sites 1 and 4, and less so at Sites 3 and 5. Furthermore, the study Site 5 was located just over a crest hill, which slightly limited sight distance to the test vehicle. Interestingly, these sites were where the more significant differences in performance were observed as a function of warning light color. Researchers hypothesize that the relatively lower overhead lighting levels (and limited sight distance at one site) made it more difficult for motorists to determine the type of vehicle that was associated with the different warning light color configurations, and so more of them tapped their brakes prior to reaching the vehicles. When overhead lighting was higher, motorists could see from farther away the type of vehicle and its location on the roadway ahead. In this situation, the warning light color configuration may have become a less critical information source for motorists, and resulted in little differences in braking applications.

Although significant differences by warning light color configuration were not always present at each site, the presence of warning lights in general did affect braking application relative to a normal (no warning light) condition. This is evident in the fact that brake application rates at three of the four sites were significantly greater than zero for all warning light color configurations, including yellow only. At Site 3, the braking percentage associated with the yellow light only was not significantly higher than zero, but was for the yellow/blue and yellow/blue/red configurations.

IMPLICATION OF RESULTS TO TXDOT VEHICLE WARNING LIGHT POLICY

It is often very difficult to detect small effects of certain traffic control devices upon traffic operations. This is because traffic operations in general are affected by a large number of other factors which cannot be controlled in an experiment such as this (i.e., driver attitudes and thought processes while driving, environmental effects, individual vehicle interactions, etc.). This may be the case with vehicle warning lights. The analysis of speeds found a few significant reductions in speeds at a few sites for a few warning light color combinations, but not all. Also, researchers observed a few more reductions for the yellow/blue light configuration than for the yellow/blue/red light configuration or for a DPS vehicle, which is a rather puzzling result. Consequently, it is difficult to draw any solid conclusions about the effect of vehicle warning lights upon vehicle speeds.

Lane choice performance measures examined in these studies (lane distributions and lane changes) were similarly inconclusive as to any consistent effects of warning light color configuration. However, analysis of brake light applications did indicate a trend towards increased brake usage for the red/yellow/blue light configuration relative to the yellow light only configuration. There was also evidence that the yellow/blue light configuration may also result in slightly greater frequency of brake applications, although not as dramatic a change as for the red/yellow/blue configuration. As would be expected, the presence of a law enforcement vehicle (DPS) generally resulted in significantly higher frequencies in brake light activations.

The fact that speeds were lower at two sites when the yellow/blue light configuration was tested suggests that this combination can have the desired speed-reducing effect in some instances. This would suggest a need to maintain current TxDOT policy to allow blue and yellow lights to be used together on those vehicles used for activities that place workers or the public in particularly hazardous situations. However, since this speed reduction did not continue to be seen when the more elaborate yellow/blue/red light configuration was displayed or even when a law enforcement vehicle was used, one has to question whether those reductions were truly influenced by the presence of the warning lights or by some other factor.

Researchers believe that the brake light activations may actually be a more pure measure of the potential impact of warning light color configurations upon driving behavior. Here, a definite trend towards increased motorist response frequency is evident as colors are added to the basic yellow light used on most service (construction, maintenance, utility, etc.) vehicles. Furthermore, the presence of other enforcement cues (i.e., the law enforcement vehicle) further increases this response by motorists. According to these data, the combination of yellow and blue lights may have some incremental benefit above and beyond that of a yellow light only.

4. SAFETY OF PAVEMENT DATA COLLECTION ACTIVITIES

INTRODUCTION

The pavement data collection process usually involves vehicles traveling at normal/near normal speeds or operating under stop-and-go slow speed conditions. In addition to these planned vehicle operations, other safety hazards might require erratic maneuvers (i.e., sudden acceleration or panic stops). This warrants extreme care in retrofitting and operating data collection vehicles to ensure the safety of the motoring public, vehicle occupants, and data collection equipment. The focus of this part of the research project was to assess concerns voiced by operators and to develop recommendations for improving safety of the data collection systems.

CONCERNS OF DATA COLLECTION PERSONNEL

Through the interview process, TTI requested the following information from data collection personnel:

- Equipment operations,
- Weather conditions in which the equipment may be operated,
- Types of traffic control used,
- Procedures used to enter and leave a travel lane,
- Speed of operation,
- Personnel required to perform the tasks,
- Ideas for improvements, and
- Safety concerns.

These interviews yielded a number of user concerns related to pavement data collection operations. These are listed below:

1. The visibility and reliability of rotating beacons,
2. The need to provide timely information to motorists about the activity,
3. The safety of equipment mounted inside the vehicles,
4. Rear visibility for certain vehicles and types of equipment,
5. Externally mounted equipment that sticks out of the vehicle,
6. Equipment added at districts that is not positively secured,
7. Need for better guidelines for starting and stopping a data collection convoy,
8. The training of new drivers or operators,
9. Personal safety at horizontal and vertical curves, and
10. Crashes caused by inattentive or DWI drivers.

The sections that follow critique the various pavement data collection systems and in-vehicle equipment layouts with respect to these concerns.

ASSESSMENT OF PAVEMENT DATA COLLECTION SYSTEM OPERATIONS

The pavement data collection schemes can be broken into three types of systems. The first type is pavement data collections systems traveling at normal or near normal speeds. This equipment includes the siometer, profiler, profilometer, multi-functional vehicle (MFV), skid system, and the ground penetrating radar (GPR). The second type is stop-and-go operations which includes the Dynaflect and falling weight deflectometer (FWD). The third type is the mobile load simulator (MLS). This data collection device involves major setup time, testing time, and several pieces of external equipment.

Category 1: Near Normal Travel Speed Activities

The first category of pavement data collections systems is the equipment that moves at normal or near normal traffic speeds. This includes the siometer, profiler, profilometer, MFV, skid truck, and GPR. The siometer is the older of the equipment used to measure pavement serviceability. The vehicle operates at or near posted road speeds and requires a crew of two (a driver and an equipment operator). The profilometer is a van-mounted pavement serviceability measuring device that uses laser sensors that reflect off the pavement to detect bumps in the road surface. This vehicle also operates at or near posted speed limits. Finally, the profiler is similar to the profilometer van in that it is a van mounted pavement serviceability measuring device that uses laser to detect changes in the road surface. In the profiler, both the acoustical and the laser sensors are mounted on the front bumper. The device extends across the entire width of the front of the vehicle, and slightly out in front of the bumper.

Generally speaking, this category of equipment does not appear to suffer from many of the safety concerns expressed above by data collection personnel. Basic guidelines indicate that this equipment can only be used in daytime conditions (30 min after sunrise to 30 min before sunset) on dry roads with good overall visibility. Since these vehicles travel near normal traffic speeds, traffic control needs are minimal above normal vehicle lighting (such as rotating beacons or flashing strobes) and signals. Maneuvers into and out of traffic lanes are accomplished with caution turn signals.

One possible difficulty does exist with the profiler equipment positioned in the front of the research van. Specifically, the width of the device and its slight extension of the front of the vehicle does have the potential for being bumped by passing vehicles, particularly if they begin to move back into the travel lane too soon after passing. Researchers believe that a small reflector should be added to each side of the two sensors that extend past the vehicle during data collection activities. This small addition would add extra visibility to the corners of the equipment and assist motorists in maneuvering around the research vehicle.

The MFV is a data collection vehicle that has been developed by the requirements of TxDOT and is still under development. The MFV collects data in three distinct categories: 1) network level survey with real-time ride/rut summary information and video, 2) network level surveys with real-time ride/rut summaries, and 3) project level surveys with longitudinal and transverse profile measurements and project level video. Similar to the profiler, the primary concern for the MFV is the equipment mounted on the front of the vehicle that stretches the entire width of the vehicle. As noted above, researchers suggest that a small reflector be added to each side of the sensors that extend outside the vehicle during data collection.

The skid system is used to collect highway surface friction data. It travels at normal to near normal traffic speed and is served by one person for driving and operation. The automatic data collection process involves squirting water on the pavement, locking up the trailer tires over that section of water, and measuring the resulting friction. With respect to traffic control and operational safety, a small concern does exist about the water spray placed on the pavement during the friction test. Since the truck operates at normal travel speeds, the sudden presence of water may surprise a motorist following closely behind. It is conceivable (although the risk appears to be rather slight) that he or she could react with an abrupt braking or steering maneuver and lose control of their vehicle. An informational sign to warn following motorists of the potential for water (i.e., "CAUTION--WATER SPRAY" or similar message) is attached to the back of some of the skid trucks in the state. Researchers believe this should be required on all skid trucks being used.

The GPR system is used to collect pavement layer and condition information. The equipment used to store and analyze the incoming data is mounted in a full size van. Preparation includes mounting a 1.8 m (6 ft) boom on the front of the vehicle and attaching the radar antenna to it. The biggest concern while collecting data with this van is with the radar antenna and mounting boom. Equipment operators have noted problems with motorists changing lanes extremely close to the front of the radar van and the protruding equipment. Researchers think that attaching a flag to the front corners of the vehicle (possibly attached to the bumper) would call attention to the front of the vehicle and the protruding antenna. The height of the flags would have to be kept low so as to not interfere with driver visibility. Another alternative is to utilize signing on the back of the vehicle. In Florida, data collection personnel use a magnetic sign with the words ("CAUTION TESTING") on the back of their GPR van. TTI researchers believe a sign such as this could be used in Texas as well, but should be modified to provide more concise information to motorists. For instance, two magnetic sign panels, one on each door of the van, could display the following:

CAUTION TEST VEHICLE	EQUIPMENT IN FRONT

Category 2: Stop-and-Go Data Collection Activities

The second type of data collection equipment includes the Dynaflect and the FWD devices. Both of these are used for collecting pavement stiffness data, although the Dynaflect equipment is gradually being phased out in favor of the FWD. To collect data with the Dynaflect, the vehicle stops and then the trailer puts a low-frequency continual vibration into the road. The vibration is then received by geophones and recorded by the electronic equipment. Rubber-coated metal wheels placed on the pavement from the bottom of the trailer, and pulled along the roadway at about 32 kmph (20 mph) create the vibration. To collect data with the FWD, operators stop the vehicle and lower a 0.3 m (1 ft) circular plate to the pavement surface. Data is collected by dropping weight on the loading plate and measuring the force at the load plate and the resulting pavement deflection. Generally, once stopped, the data collection process takes 3 to 5 min to complete. This process is continued at 6 to 150 m (20 to 500 ft) intervals over a section of roadway up to 32 km (20 mi) long.

These types of activities are the most difficult to treat from a traffic control perspective. In general, they fall in the mobile work category of traffic control plan requirements (*6*). These requirements vary depending on the type of roadway on which data is being collected, but generally involve the use of shadow vehicles, truck-mounted impact attenuation devices, and arrow panels (in either directional or caution mode as dictated by the type of roadway). On multilane divided highways, a vehicle on which a LANE BLOCKED sign (FCW20-6) is mounted is driven on the shoulder approximately 450 m (1500 ft) upstream of the first shadow vehicle.

However, the fact that these devices stop intermittently or travel at fairly low speeds creates special problems on urban freeways because these roadways involve both high-traffic volumes and high speeds. Oftentimes, headways (spacings) between vehicles are short, such that a following motorist cannot see an adequate distance ahead. If the vehicle in front waits to move out of the lane until it is rather close to the shadow vehicle, the motorist following may be surprised and have to make a quick decision and maneuver to avoid the shadow vehicle. This can be especially problematic for passenger vehicles following immediately behind a large truck.

In the interest of safety, many districts put out a lane closure for a mobile operation on an urban freeway, coning off as long a section as can be worked on in an hour or so. They then move the beginning of the closure downstream and continue working in this manner until the work activity is completed. Research has shown the importance of the channelizing devices which create the lane closure taper in obtaining proper motorist response to vacate the closed lane (*7*). In addition, many urban areas (San Antonio and Fort Worth, in particular) have installed lane control signals over the travel lanes. These signals, controlled at the traffic management center (TMC), can be changed to indicate that a lane is closed downstream. Pavement data collection personnel should coordinate their work activities not only with the local district maintenance office but with these local TMCs as well.

Category 3: Stationary Data Collection Activities

The last data collection device discussed is the MLS. The time required for an accelerated pavement test under optimal conditions is currently three months. Installation of the MLS is a major undertaking requiring oversize permits, long-term lane closures protected by concrete median barriers (CMB) and full advance signing, and more. Consequently, the traffic control plan at this type of data collection location is as extensive as any other long-term construction project. However, in the interviews of the MLS operators, one concern that was noted involved public curiosity about the device. Specifically, when the MLS is first installed on a section of road, the public has a tendency to stop on the road to ask personnel present about the purpose and operation of the device. In fact, this type of event occurred during one time researchers were present observing the operation of the device. The motorist actually stopped in the travel lane and asked for an explanation of the device. Such behavior is clearly undesirable from a safety standpoint.

Obviously, it is critical that the overall traffic control set up at a site for this activity provide adequate sight distance to the closure. However, it is also desirable to attempt to provide adequate sight distance to the MLS itself if possible so that anyone who inadvertently stops in the road does not create an unseen hazard to approaching motorists. At the same time, it appears beneficial to try and discourage such stopping behavior in the first place. Researchers recommend the use of portable changeable message signs (CMS) as part of the advance warning signing. The CMS would be positioned 150 to 1000 m (500 to 3700 ft) upstream of the first advance warning sign, depending on roadway type (data collection personnel should refer to the TxDOT standard traffic control plans for the appropriate CMS location for a given facility). Once in place, researchers recommend a two panel message be displayed, each panel approximately four seconds long:

PAVEMENT TESTING AHEAD	DO NOT STOP IN LANE

ASSESSMENT OF IN-VEHICLE PAVEMENT DATA COLLECTION EQUIPMENT

During discussions with data collection personnel, researchers focused primarily on how various pieces of equipment were secured within the vehicle, and how those methods of securing equipment would behave in the event of severe deceleration, or rollover due to a crash. Methods for securing equipment in the vehicles include the following:

- Bolts with or without metal brackets,
- Straps or bungee cord,
- Velcro, or
- Clips (typically to a table top).

Figure 1 illustrates a case where researchers believe one of the mounting methods may be deficient. The monitor is secured to the table using a mounting bracket designed for home or office use. The mounting is secured to the monitor housing which is made of plastic. This plastic is not believed to be of sufficient strength to withstand high forces (such as during a sudden deceleration or rollover situation). The bracket could separate from the monitor in this situation, and the monitor could become a dangerous projectile.

Figure 1. Example of Potential Monitor Mounting Bracket Problem

Another concern noted during the research vehicle critique was with how the tables were secured to the vehicle. Typically, a desk or table is secured by using bolts only to the vehicle floor. This restraint is sufficient for normal driving conditions. However, any sideways movement of the vehicle will cause the tabletop to oscillate left and right. These oscillations can become more pronounced when heavy equipment, whose center-of-mass is above the table, is secured to the tabletop. When this happens, two types of forces will act on the legs of the table:

1. Forces pulling the bolts upward, and
2. Forces that will have a tendency to bend the table legs.

Under severe conditions (collision and/or rollover), there is a possibility that the legs will either bend or become loose (due to a broken bolt or to the bolt pulling through the sheet metal of the table legs or vehicle floor). This potential hazard can be virtually eliminated simply by additionally bolting the top part of the table to the vehicle frame. The same safety rule can be applied to any cabinet/table used for setting or mounting data collection equipment.

Figure 2 illustrates another case where a computer desk is being used for the electronic equipment and deficiencies are believed to exist in terms of how equipment is secured within the vehicle. Again, the computer monitor is strapped to brackets that are secured to the table using screws. This method of securing the monitor is sufficient for normal vehicle movements (forward or reverse) but may not be sufficient for movements or forces perpendicular to the monitor screen. For instance, the monitor might slip out and become a projectile in a side-impact or rollover situation.

Figure 2. Example of Unsecured Equipment in Research Vehicle

Researchers also note that there are unsecured items (equipment, papers, aerosol can, etc.) under the table and between the table and the driver seat in Figure 2. Under normal driving conditions, this does not pose any significant safety threat. However, under extreme conditions, loose items may be potentially dangerous to the vehicle occupants. According to basic laws of dynamics, the force with which a moving object hits something in its path is dependent on the velocity at the time of impact and the mass of the object. Thus, a small object moving at a high velocity can be as dangerous as a larger object moving slowly.

The top-left corner of Figure 2 shows a section of mounting boom for the ground penetrating radar when it is transported inside a vehicle. It is 1.8 m (6 ft) long and has a significant weight. The boom is stored in the vehicle in a full length U-bracket. This bracket is secured to one side of the vehicle and has plates at the two ends to prevent the boom from sliding out. However, the center-of-mass of the boom is located at a point that is higher than the top edges of the U-bracket. In addition, the radar boom is not secured to the bracket. Under normal driving conditions, the weight of the boom will keep it inside the bracket. However, there is a possibility of the boom falling out if the vehicle traverses a large bump, or if the vehicle is involved in a rollover situation. Thus, researchers strongly recommend that a metal locking bracket or other sort of mechanism be used for properly securing the boom to the vehicle.

TxDOT staff informed the researchers that there have been instances where some pavement data collection equipment was not installed at the design shop, but rather placed in the vehicle at the district where it was used. This can lead to instances of unsafe equipment storage and installation. TxDOT can avoid such situations by developing a policy that provides districts with design/installation guidelines (such as provided in this chapter) for installing additional equipment in the research vehicles.

Researchers were also informed that it is also not uncommon to carry unsecured weights for the FWD inside a vehicle. Under normal driving conditions, these unsecured items may not pose any threat but may turn into deadly projectiles in collision or rollover conditions. Researchers also strongly suggest that provisions be made to secure all such items and that the operators secure all items before using a data collection vehicle.

As a final note, one fatal incident was reported to the researchers. In this incident, an operator was working at computer desk while the vehicle was parked. This person died when he was pushed into the desk due to another vehicle colliding with the data collection vehicle. This person was not wearing a seat belt. Operators and drivers of data collection vehicles must always be aware of safety and take standard precautions such as wearing seat belts properly when collecting data.

5. SUMMARY AND RECOMMENDATIONS

SPECIAL VEHICLE WARNING LIGHTS

Implications of Findings

The results of this research cannot fully lay to rest the concerns expressed by state law enforcement officials regarding the overuse of blue lights on TxDOT or other service vehicles, a subsequent driver disregard for that color, and an eventual degradation of safety for both authorized emergency and service vehicle equipment. However, survey results from Chapter 2 suggest that most motorists key on a combination of blue and red lights to indicate the presence of law enforcement, and focus on the warning light color red alone or red and white combinations to indicate other types of authorized emergency vehicles (i.e., fire trucks, ambulances). Consequently, the presence of blue lights in conjunction with yellow lights on service vehicles for TxDOT does not appear to conflict with motorists' interpretations of any of the currently authorized emergency vehicles within the state.

TxDOT policy also allows red warning lights to be used on vehicles, as long as they are not displayed to the front of the vehicle. Again referring to Chapter 2, a yellow and red color combination is not commonly associated with any authorized emergency vehicle either, and conveys a strong sense of hazard to motorists as they approach a vehicle with that color combination. In the event that legislation is passed to prohibit the use of blue warning lights by TxDOT and other service vehicles, the use of yellow and red light combinations should be considered for those vehicles now utilizing a yellow and blue light combination.

Current TxDOT policy to allow yellow, blue, and red lights on courtesy patrols conflicts with a small (13 percent) portion of motorists who expect to see this color combination on enforcement vehicles. However, both courtesy patrols and law enforcement vehicles can play very similar roles in incident response (i.e., disabled vehicle protection, traffic control assistance, etc.). In fact, the motorist assistance patrol in Houston utilizes law enforcement officers to man the patrols, and so employs an authorized emergency vehicle warning light color configuration. For the sake of consistency across the state, a similar warning light color configuration for all types of courtesy or other incident response vehicles (regardless of whether they are manned by TxDOT or law enforcement personnel) would be expected to promote more consistent interpretations by motorists statewide.

TxDOT Vehicle Warning Light Policy Recommendations

In general terms, the current vehicle warning light policy does appear to be justified in allowing certain types of vehicles to utilize both blue and yellow lights. Field personnel have contended for some time that the presence of the blue lights in conjunction with standard yellow lights does affect driving behavior. This information is supported by some (but not all) of the traffic operational data collected through this research. At the same time, statements which allow vehicles to use one pair of yellow or red flashing warning lamps (facing to the rear) in conjunction with a yellow omnidirectional warning light on the cab of the vehicle also appear justified through this research. Discussions with members of the Project Advisory Committee indicate that a yellow and red warning light combination is not currently used extensively within TxDOT (although it is used by certain private tow truck operations).

Specific recommended changes to the current warning light policy are enumerated below.

1. Researchers believe that the decision of whether a particular type of vehicle or piece of equipment should be outfitted with both blue and yellow lights should continue to be based on the risk that using the vehicle/equipment for its intended function places upon workers and/or the motoring public. It is recommended that the policy regarding blue lights be expanded to explicitly state those characteristics which are judged to warrant the additional blue warning light color. Statements to support the currently approved vehicles in the policy should read something like the following:

    - Blue lights are intended to be applied to a vehicle or piece of equipment used for any activity that requires workers to be out of the vehicle while in a lane of traffic and without the presence of channelizing devices upstream of the vehicle to close the lane.

    - Blue lights are intended to be applied to a vehicle or piece of equipment used in a moving operation in a travel lane that travels at a speed of less than 6 kmph (4 mph) or more than 50 kmph (30 mph) below the operating speed of traffic on a roadway (note: the actual number used to define this criteria could be changed).

2. Researchers recommend that the statement allowing the use of blue lights by maintenance foremen and assistant maintenance foremen be changed or eliminated. This statement has created negative feelings IN other TxDOT personnel within the state who feel that it implies a greater sense of concern for the foremen/assistant foremen than other workers. Researchers suggest the statement be reworded to allow blue lights on vehicles used for incident response activities (as opposed to incident removal or clean-up activities), regardless of who utilizes those vehicles. This statement would cover both the motorist assistance (courtesy patrol) and foremen/assistant foremen vehicles explicitly mentioned now in the policy. As a second option, the statement regarding maintenance foremen or assistant maintenance foremen could be embellished to indicate (possibly in parentheses) that "other personnel using these vehicles are allowed to activate the blue lights for the above-mentioned purposes."

3. A final recommendation regarding TxDOT's vehicle warning light policy concerns the special needs of motorist assistance (courtesy patrol) vehicles. Researchers recommend

that legislation be proposed to designate TxDOT-authorized incident response vehicles as authorized emergency vehicles under Section 541.201 of the Texas Transportation Code (*1*). This would ensure that these types of vehicles would continue to be able to utilize the reserved vehicle warning light colors reserved for authorized emergency vehicles. Furthermore, this legislation would offer additional protection to the response vehicles in terms of preferential right-of-way and minimum following distances by motorists that would enhance the effectiveness and safety of the courtesy patrol vehicles.

PAVEMENT DATA COLLECTION ACTIVITIES

Recommendations for External Equipment

1. Place reflectors on all equipment that extends past the data collection vehicles to make the vehicles more noticeable to motorists.

2. Place Fresnel lenses on the back of all rear windows of data collection vehicles to provide drivers with better visibility.

3. Consider the use of magnetic signs during testing to inform the public that tests or measurements are being performed by personnel in the vehicle. Specifically, a two-panel magnetic sign was suggested in this research for the GPR:

CAUTION TEST VEHICLE	EQUIPMENT IN FRONT

4. The older FWD units need to have the trailer retrofitted so that any necessary extra weights can be carried can be done so on the trailer rather than in the data collection vehicle.

Although not specifically discussed in this report, data collection personnel should also consider requesting assistance from law enforcement officials when collecting data on high-speed, high-volume roadways. Pavement data collection activities should also be coordinated with the appropriate maintenance section in each district to ensure that adequate traffic control procedures are being followed for the roadway and traffic conditions that are present.

Recommendations Regarding In-Vehicle Equipment

The following specific recommendations are offered for consideration regarding safety improvements inside pavement data collection vehicles:

1. Ensure that all equipment and instruments are fully secured. These items include tables and cabinets for mounting and setting equipment. When mounting brackets are bolted to pieces of equipment, consideration should be given to the structural integrity of that equipment housing. Bolts through plastic housing are likely to pull loose in the event of a crash and thus allow the equipment to fly through the vehicle cabin. This significantly increases the potential for bodily injury to data collection personnel.

2. Install top-loading, fully secured storage bins for smaller items. These bins should be tall enough to ensure that rolls of plans, paper, and other items stay inside during vehicle operation.

3. Each cabinet or table should be securely bolted to the vehicle floor as well as to the side of the vehicle. The vehicle frame can be used to secure the top of these items to the vehicle.

4. Removable items that are usually set on the floor (i.e, first-aid kit, tool box) should be strapped to the vehicle. For this purpose, vehicles should be equipped with straps at several locations.

5. During the data collection process (vehicle moving or stopped), each occupant should use a safety belt when inside the vehicle.

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